OSIRIS-REX EARTH RETURN & ENTRY: NAVIGATION OPERATIONS & LESSONS-LEARNED

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The Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) spacecraft successfully returned to Earth on September 24, 2024, safely delivering its Sample Return Capsule (SRC) to the Utah Test and Training Range (UTTR). This paper describes the navigation operations that occurred between the departure from Bennu and the return of the SRC. An overview is given of the Flight Dynamics System (FDS) that includes tracking, orbit determination (OD), maneuver planning, and interfaces with entry, descent, and landing. Operational details on the SRC release criteria and conjunction assessment considerations are also provided. Lessons learned are presented that may help future sample return or interplanetary entry missions.

INTRODUCTION

On October 20, 2020, the Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) spacecraft slowly descended to the surface of the near-Earth asteroid 101955 Bennu and successfully collected hundreds of grams of pristine regolith.[1,2] After the spacecraft backed-away from the surface, the operations team immediately began the process of stowing the priceless sample in the Sample Return Capsule (SRC). With the sample safely stowed, OSIRIS-REx departed the vicinity of Bennu on May 10, 2021, initiating a roughly 2.5-year and 2-billion km journey back to Earth (see Figure 1). On September 24, 2023, OSIRIS-REx released the SRC at a distance of approximately 100,000 km from Earth. After four hours of free-flight, the SRC entered Earth's atmosphere and descend to the surface, safely touching down at the Utah Test and Training Range (UTTR) (see Figure 2). The recovery team retrieved and secured the SRC before ultimately transferring it to the Astromaterials Curation Facility at NASA Johnson Space Center (JSC).

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Earth return and entry operations required detailed analysis, planning, and coordination among multiple mission operations teams, including navigation, Entry, Descent, and Landing (EDL), spacecraft, recovery, and the range. While preparations for Earth return and entry began early in the development phases, detailed planning and analysis updates began in early 2022 and continued through sample return. Navigation operations leveraged valuable experience from interplanetary cruise and Bennu proximity operations, which included over 300 navigation ephemeris updates and over 130 propulsive maneuver designs and execution.[3] Specifically, the navigation benefited from the experience and accurate landmark tracking[4] used during the Bennu proximity operations between 2019 and 2021. The non-gravitational dynamic models influencing the spacecraft motion such as solar radiation pressure and spacecraft thermal radiation pressure were accurately and precisely characterized,[5,6] enabling improved navigation performance during return and entry. The high-cadence operations and frequent navigation updates at Bennu prepared the team for the critical Earth return phase.[7]

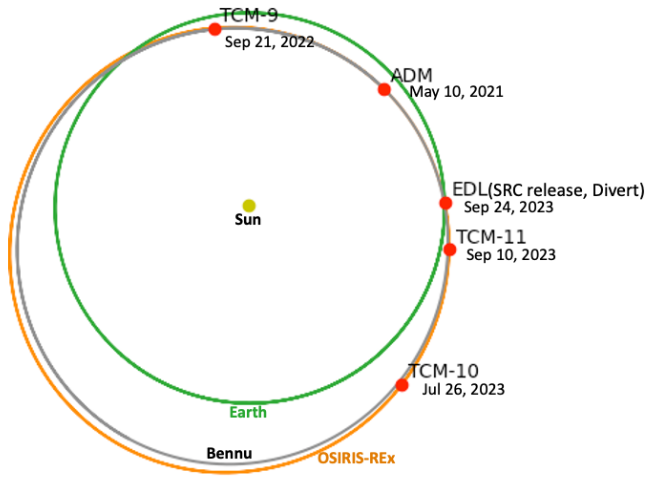

Figure 1: Earth Return trajectory

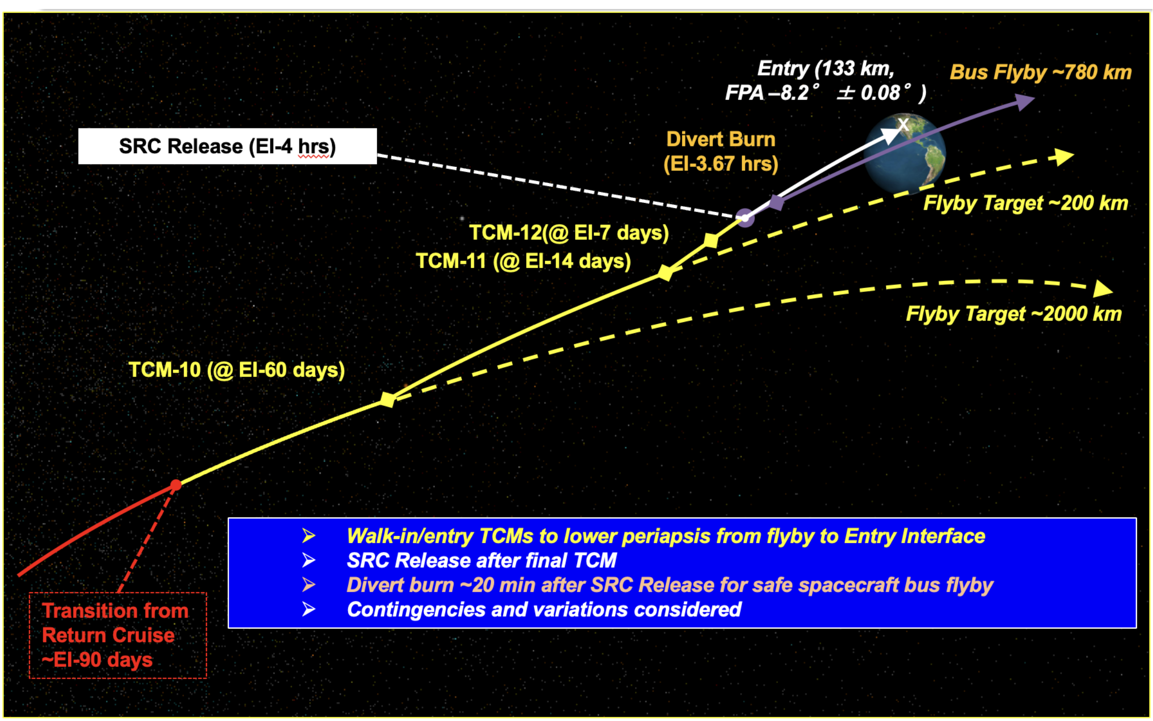

Figure 2: Graphical overview of OSIRIS-REx baseline Earth and entry concept of operations.

In this paper, we will discuss the overall Earth return and entry Concept of Operations (ConOps) for OSIRIS-REx, including navigation and EDL. We will summarize the key and driving requirements for the design and ConOps, as well as significant trade studies and updates between development and operations phases. We will present the Earth return targeting strategy and back-up maneuver options, operations timeline and delivery schedule, and interactions and interfaces between the navigation, EDL, spacecraft, and recovery teams and UTTR. Finally, we will identify notable lessons-learned and areas of improvement to help inform future sample return missions. Detailed information on the Orbit Determination (OD) performance, maneuver targeting strategy, and EDL are provided in References 8, 9, and 10, respectively.

OPERATIONS OVERVIEW

The OSIRIS-REx Flight Dynamics System (FDS), comprised primarily of navigators and analysts from NASA Goddard Space Flight Center (GSFC) and KinetX Aerospace, were responsbile for Earth entry targeting and navigation. FDS worked closely with members of the EDL team from NASA Langely Research Center (LaRC) and Lockheed Martin. Navigation and EDL operations were performed mainly from the Navigation Mission Support Area (NavMSA) hosted at Lockheed Martin Space in Littleton, CO. FDS and EDL were geographically-distributed teams and were able to support non-critical operations remotely from across the US.

FDS Requirements

The key FDS requirements for OSIRIS-REx Earth Return & Entry targeting are provided in Table 1. FDS requirements were mapped to mission Level 2 requirements as defined in the Mission Requirements Document (MRD). The third column shows FDS compliance prior to entry. All requirements were met during actual operations.

Earth Return Targeting Strategy

In compliance with the FDS/MRD requirements stated in Table 1, the goal of the Earth return trajectory was to deliver the SRC to the Earth's atmospheric Entry Interface (EI) with an atmospheric-relative speed less than 12.4 km/s and within $\pm 0.08^\circ$ of the inertial Entry Flight Path Angle (EFPA) of -8.2° before September 30, 2023. The strategy to achieve this goal, as explained by Reference 9, was to reduce the Earth flyby distance on September 24, 2023 as the mapped predicted spacecraft Earth encounter B-plane uncertainties were reduced with each consecutive burn during the 2.5-year journey. This was to keep Earth impact probability below 1% until targeting the EI for entry at two weeks out. Shortly after this point where the SRC intercepts this EI, the physics guiding the SRC trajectory change from astrodynamic to aerodynamic. The EI at Earth, which was based on the atmospheric trajectory landing on target in UTTR, was set on September 24, 2023 at 14:43:04 TDB, when spacecraft reached the 6503.142 km radius from Earth center, or approximately 133 km above Mean Sea Level (MSL), with inertial (J2000) EFPA of -8.2°.[9] At one minute before EI, the FDS team hands off the SRC state and Monte Carlo (MC) dispersed states in the Entry State File (ESF) to the EDL team who then propagates the SRC nominal and dispersed trajectories through the atmosphere using the Program to Optimize Simulated Trajectories II (POST2)[11] to the landing site in the UTTR. The POST2 software integrates the dynamics of the SRC from atmospheric entry through peak heating, peak deceleration, drogue and main parachute deployment, and landing in

Table 1: FDS Key & Driving Requirements for Earth Return & Entry

Req. #	Statement	Compliance (Prior to Entry)
FDS-F-77 (MRD-77)	The FDS will adhere to the Design Reference Missions (DRM) and Navigation plan.	Requirement satisfied by mission design.
FDS-F-18 (MRD-18)	The FDS will design a trajectory that safely lands the Sample Return Capsule at the UTTR no later than September 30, 2023.	Requirement satisfied by nominal mission design. Back-up trajectory option requires a waiver (September 2025).
FDS-F-177 (MRD-177)	The FDS shall, beginning prior to launch, participate in the planning of Operations Readiness Tests (ORTs) for the Earth Return & Recovery mission phase beginning at Landing – 2 months or earlier.	All ORTs (nominal and off-nominal) completed successfully.
FDS-F-163 (MRD-163)	The FDS shall design a trajectory to return the Sample Return Capsule with an Earth atmosphere-relative re-entry speed no greater than 12.4 km/s.	Requirement satisfied by mission design (V_{entry} = 12.38 km/s). Expected velocity dispersions are well below 0.02 km/s.
FDS-F-32 (MRD-32)	The FDS shall design a trajectory that places the Flight System on an Earth return trajectory that misses Earth by $>$ 200 km until the final deterministic maneuver before Sample Return Capsule release.	Requirement satisfied by mission design, with final deterministic maneuver occurring at Earth Interface minus 14 days (TCM-11).
FDS-F-33 (MRD-33)	After Sample Return Capsule release, the FDS shall design a sequence of maneuvers to place the Flight System in a solar orbit with a closest approach to Earth, Moon, or any other solar system body restricted by Planetary Protection, of $>$ 250 km.	Requirement satisfied by mission design, Earth periapsis following divert approx. 780 km.
FDS-F-34 (MRD-34)	The FDS shall design a trajectory for the SRC to re-enter on a direct posigrade trajectory, with an inertial flight path angle of $-8.20° \pm 0.07°$ (3σ) at an entry interface of 6503.14 km from Earth center, for landing at the UTTR.	Requirement satisfied by mission design and navigation analysis. $\pm 0.07°$ (3σ) is allocation to FDS without consideration of SRC release error. However, overall error of $\pm 0.08°$ (3σ) is also met.

6-Degrees-of-Freedom (DOF). Table 2 lists the Earth Return maneuvers and their final design ΔV magnitudes. The nominal Earth targeting strategy beginning with the post-Trajectory Correction Maneuver (TCM)-9 2000-km flyby through entry and divert is illustrated in Figure 2. Additional details on the maneuver design are found in Reference 9.

SRC Release was set to occur at EI-4 hours, with the Earth divert maneuver executed 20 minutes later (EI-3.67 hours). The spacecraft could autonomously delay SRC release by up to one hour if any anomalies were encountered during the SRC release sequence execution onboard, which would have resulted in a corresponding delay to the divert burn. The divert burn was originally intended to singularly raise the Earth periapse distance of the spacecraft bus after SRC Release to higher than 250 km, but now additionally targets the location of the first Origins Spectral Interpretation Resource Identification Security APophis EXplorer (OSIRIS-APEX) extended mission[12] Deep Space Maneuver (DSM) in July 2024, which also provides a perigee altitude of 780 km.

The FDS and EDL teams began preparations for September Earth Return activities (maneuver designs, EDL analyses, and various deliveries) with internal interface, frame verification, and navigation training exercises. Afterward, FDS and EDL participated in two Operations Readiness Tests (ORTs) with the Spacecraft Team (SCT) and project management teams; one nominal and one off-nominal held, respectively, five and four months before EDL. Another ORT, held 1-month

Table 2: As-Flown Maneuvers for Earth Return & Entry

Maneuver	Epoch	ΔV [m/s]	Notes
ADM	10-May-2021	265.9	Bennu departure Target 10000-km Flyby
LTR-1 Cals.	June 17 2022	0.02, 0.01, 0.005	2 sets of each magnitude along Earth line
LTR-1 Cals.	June 25 2022	0.02, 0.01, 0.005	1 set of each magnitude along Earth line
LTR-2 Cals.	July 1 2022	0.02, 0.01, 0.005	1 set of each magnitude along Earth line
ACS Cals.	July 9, 2022	0.25, 0.25	1 along and 1 orthogonal to Earth line
TCM-9	21-Sep-2022	0.264	Target 2000-km Flyby
TCM-10	26-Jul-2023	0.570	Target 200-km Flyby
TCM-11	10-Sep-2023	0.240	Target Entry Interface
TCM-12	17-Sep-2023	0.003	TCM-11 Clean-up
TCM-13	23-Sep-2023	N/A	Contingency Clean-up (waived)
CAM	24-Sep-2023	N/A	Contingency Collision Avoidance (waived)
Divert	24-Sep-2023	65.5	Optimized for extended mission

before entry, was mainly focused on the SRC recovery from the range at UTTR. Three Operations Proficiency Integrated Exercises (OPIEs), the last of which was held 1-month prior to entry, exercised the programmatic 'Go or No-Go' decision meetings discussed below.

Navigation Tracking

For successful targeting and reconstruction of the Earth return maneuvers, a robust strategy was implemented to acquire a sufficient quantity of radio-metric tracking to first determine the spacecraft state and predictive force models as precisely as possible and then to reconstruct the maneuver as accurately as possible. This strategy relied on increasing the frequency of tracking and Delta-Differenced One-Way Range (ΔDOR) passes in the 3–4 weeks before and after the maneuver execution. Nominally in cruise, the navigation team required three 8-hour passes (24 hours total) per week to adequately trend OD solutions during quiescent cruise with weekly spacecraft momentum desaturations. In general for maneuvers, the navigation team required an increase to five 8-hour passes per week (or a weekly total of 40 hours) beginning 4 weeks prior to the maneuver through 3 weeks after with continuous coverage for 1 day before and after execution. Alternating tracking passes among the three Deep Space Network (DSN) complexes was preferred as much as possible. Furthermore, the navigation team required at least 3 ΔDOR passes per week in the 3 weeks before the Data Cut-Off (DCO), through burn execution, and 2–3 weeks afterwards. Preferably, the measurements would include both the North-South (N-S, Goldstone-Canberra) and East-West (E-W, Goldstone-Madrid) baselines; however only N-S baselines were available in 2023 prior to entry due to the spacecraft's southern declination relative to Earth. The Canberra view period extended over 13 hours during this low declination period. ΔDOR passes were generally 1-hour in duration.

For the final 2-3 months of return cruise, as discussed below, the frequency and total amount of tracking steadily increased beyond these general tracking requirements to further ensure our navigation accuracy and provide robustness to loss of any single Deep Space Station (DSS) station or complex. In terms of OD performance, requirements could likely have been met with slightly less tracking, e.g., 50% less 2-way radiometric tracking and 2 versus 3 ΔDORs in the final two weeks prior to entry, but the additional tracks and data provided margin and robustness. Reducing tracking to below levels requested by the navigation team would have warranted further analyses.

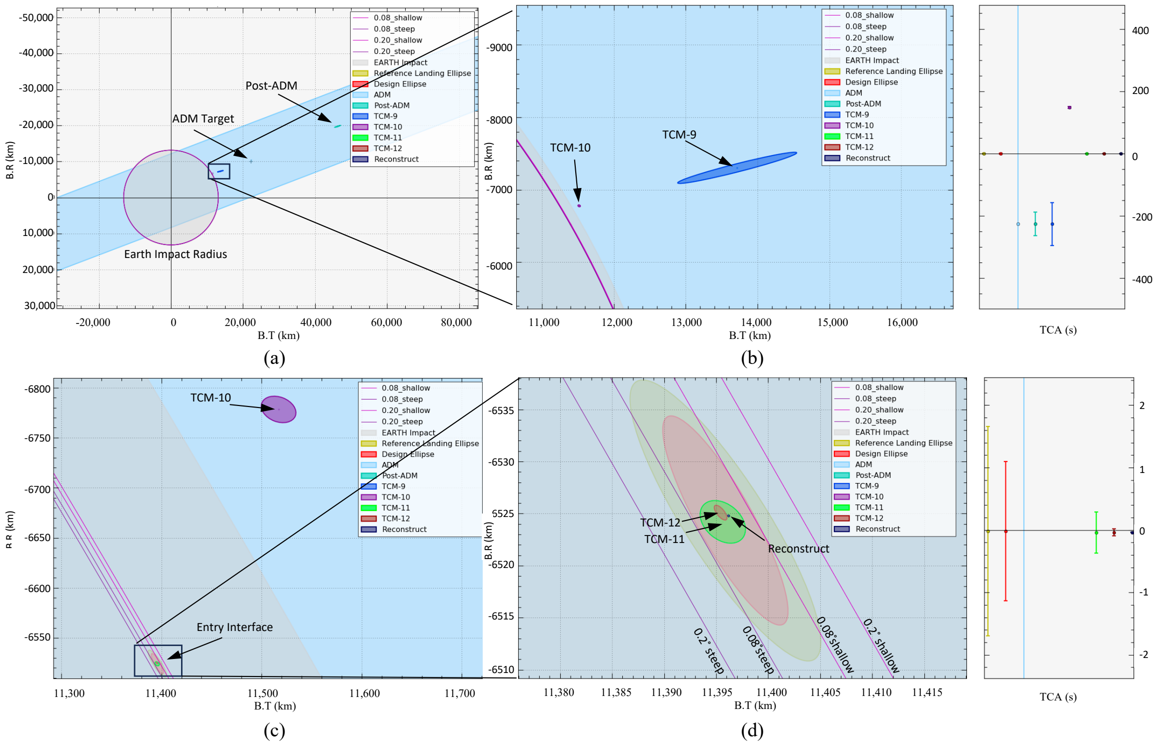

Figure 3: 3σ Earth-centered Earth-Mean-Equator and Equinox of J2000 B-plane showing Asteroid Departure Maneuver (ADM) target and result (a), TCM-9 target (b), TCM-10 target (c) relative to Entry Interface time on September 24, 2023 14:43:04 TDB and mapped landing reference and requirements, TCM-11, 12 targets and Post-EDL OD reconstruction (d).

Navigation Operations Plan & Schedule

After the completion of the Post-Touch-and-Go (TAG) Observation flyby of Bennu on April 7, 2021, the spacecraft drifted from the asteroid before Earth return cruise activities began with the design, build, and test of the Asteroid Departure Maneuver (ADM) starting with DCO on May 3, 2021. At a distance of 359.5 km from Bennu, the main-engine ADM executed on May 10, 2021 at 20:00 UTC, targeting Earth return. ADM moved the spacecraft Earth close-approach distance from 0.5 au on Aug 25, 2023 to nominally 10,000 km on September 24, 2023. Figure 3a shows the ADM target and acheived position in the Earth-centered B-Plane relative to the Earth impact radius on September 24, 2023. The elongated, cyan ellipse (truncated) represents the 3σ trajectory uncertainties from the expected ADM errors with dimensions of 521,500 km x 9,565 km and a linear flight time uncertainty of 37,100 sec. The accurate ADM performance ($<<1$ cm/s $|\Delta V|$ and $< 0.1^\circ$ pointing error) resulted in a 35,000 km altitude flyby with zero impact probability.

Following ADM, the spacecraft completed nearly 2 complete orbits around the Sun by the time of EDL, as shown in Figure 1. The spacecraft heliocentric distance ranged from 0.89–1.4 au. The spacecraft operated during an extended solar conjunction period with Sun-Earth-Probe (SEP) angles under 10° from December 8, 2020 until November 15, 2021. The spacecraft entered deep conjunction, with SEP angles below 2°, between September 19 and October 12, 2021 and below 1° between September 26 and October 6, 2021. Ranging is disabled for SEP angles under 2°; coherent 2-way Doppler tracking is suspended under 1°. From April 5 to July 24, 2021, the spacecraft

solar distance was under 1 au with perihelion at 0.89 au on May 30, 2021. From July 1, 2022 until October 17, 2022, the spacecraft solar distance remained under 1 au with perihelion at 0.89 au on August 25, 2022. High-Gain Antenna (HGA) is prohibited for heliocentric distances under 1 au due to thermal constraints. Though much noisier, ranging using the +X Low-Gain Antenna (LGA) was available during these periods. The spacecraft reached an aphelion distance of approximately 1.4 au on January 11, 2022 and again on April 10, 2023.

There were several ADM cleanup burn opportunities, ADMa-d, scheduled 2 and 7 weeks (May 24, 2021 and June 21, 2021) and 6 and 10 months (November 23, 2021 and March 22, 2022) after execution. Due to the accurate ADM performance, these cleanup maneuvers were canceled since there was no significant ΔV savings for executing a clean-up maneuver versus proceeding directly with TCM-9 on September 21, 2022.

Thruster calibration activities were scheduled in mid-June to early July 2022 when the Sun-Earth-spacecraft geometry was favorable for reconstruction. These calibrations were used to test the performance of the Low-Thrust Reaction Engine Assembly (LTR) and Attitude Control System Turn-Burn-Turn (ACSTBT) thrusters after the large mass loss due to the expenditure of propellant from ADM. Two days, June 17 and 25, were devoted to testing the LTR-1 thruster at ΔV magnitudes of 2, 1 and 0.5 cm/s. Each magnitude test was executed three times over these two days. To minimize the impact of a LTR-1 failure, the secondary LTR thruster, LTR-2, was exercised on July 1, 2022 at ΔV magnitudes of 2, 1 and 0.5 cm/s. The LTR calibrations were oriented directly along the Earth line of sight. The ACSTBT calibration consisted of two 25 cm/s maneuvers, one directed along Earth line and one orthogonal to Earth line, both executed on July 9, 2022. Reference 9 discusses the performance of these calibrations and their impact on TCM-9 in more detail.

TCM-9 executed on September 21, 2022 to target a 2000-km flyby of Earth on September 23, 2023. The TCM-9 Earth B-Plane target and 3σ uncertainties (2330 km x 247 km, $\pm$77 sec) are shown in Figure 3b). The backup TCM-9 date was scheduled for October 12, 2022. The final tracking data cutoff was on September 12, 2022. At this time, the spacecraft attitude plan was nominally Sun-pointed with the spacecraft +X axis, including the HGA, pointed towards the Sun. Three times per week, the spacecraft slewed to point the HGA towards Earth for 1–4 hours. From July 2022 to November 2022, the spacecraft-Sun distance was under 1 au, which required the spacecraft to perform two momentum desaturations per week to manage angular momentum.

Three weeks ahead of TCM-9, 3 ΔDOR observations were acquired per week with both N-S and E-W baselines. However, the tracking schedule was impacted by the Artemis-1 launch attempt that was originally scheduled to occur on August 29, 2022, with back-up launch opportunities on September 2 and 5. Although the launch was scrubbed, the last 2 ΔDORs in support of the TCM-9 final design were deleted from the schedule. The acquisition of 2-way radio-metric data was also severely impacted with average of 12.2 hours per week in the two weeks before the TCM-9 DCO, compared to the original requirement of 40 hours per week. The tracking schedule, however, did include 6 additional ΔDORs through October 30, 2022 to support a the backup maneuver opportunity that was ultimately not needed.

TCM-10 executed on July 26 to target a lower Earth flyby distance of 200 km. The TCM-10 Earth B-Plane target and 3σ uncertainties (18 km x 12 km, $\pm$2.8 sec) are shown in Figure 3c. A backup TCM was scheduled for August 2, 2023. The backup maneuver was scheduled less than a week later on August 8, 2023 due to the spacecraft processor reboot, discussed below. Because of the short timeline between the prime and backup maneuvers, both were designed in parallel on

July 17, 2023. In addition to these maneuver designs, the post-SRC release divert burn was also designed and delivered at this time. The divert burn design, which optimally targeted the post-EDL interplanetary trajectory for the extended mission, remained fixed and was not updated based on subsequent OD solutions.

From June 1 to July 1, the DSN radio-metric tracking frequency increased to four 8-hr passes per week (32 hours total) compared to the nominal schedule of three 8-hour tracks per week. Beginning two weeks before the TCM-10 DCO, the navigation team required at least seven 8-hr tracking passes per week from July 1 through August 25. The DSN tracking schedule increased to 10 8-hour passes per week in the last week of August, then increased again to approximately 2 passes per day (16 hours) just before September 10. Following TCM-11 through EDL, the tracking increased to near-continuous coverage (18-20 hours per day) from September 21–25. Beginning June 24, 2023, three N-S ΔDOR passes were scheduled per week, increasing to approximately 4 per week from July 10 through September 1. After September 1, ΔDORs increased to 5–6 passes per week up until EDL.

At approximately 47 days from entry, after the execution of TCM-10, the spacecraft performed a reset of the onboard processor. The SCT rebooted the spacecraft to ensure the configuration of the onboard flight system was in a known state and consistent with ground test equipment. The SCT then uploaded a set of libraries to bring the system to its latest configuration. This activity took place on August 8, 2023, with August 9–10 reserved for margin. Attitude recovery during the reboot resulted in unbalanced thrusting and an accumulated $\Delta v < 0.5$ mm/s.

The last official update of the spacecraft clock correction and associated kernel file occurred near the completion of the spacecraft system reboot. Although the anticipated drift in the spacecraft clock over this period was small, the SCT estimated a correction on the ground and provided updates to FDS for the timing of TCM-11, TCM-12, SRC release, and divert.

The spacecraft remained in the following configuration following the reboot until EI-31 hours (47 days total): Sun-point attitude, solar arrays with inner and outer gimbal angles of 90°, -20°, respectively, and telecommunications over +X LGA. There were no HGA-to-Earth slews after the spacecraft reboot. At EI-31 hours, the spacecraft slewed to the SRC release attitude. Telecommunications continued on the -X LGA while in this attitude.

Weekly desaturations decreased to once per week through September 2, 2023 while the heliocentric distance was greater than 1 au. The last momentum desaturation before TCM-11 occurred on September 3, 2023. The target momentum state was biased in order to move the next required desaturation until after TCM-11. Finally, the final desataturation before EDL was scheduled 90 minutes after the nominal execution time of TCM-11. The navigation team would have preferred the final desataturation occurred before the TCM-11 DCO at EI-16 days to allow time for reconstruction prior to the final design; however, the placement was ultimately selected to balance the interests of navigation and attitude control, ensuring a nominal system momentum state during the SRC release period.

Post-TCM-11 Through EDL

Figure 4 shows a high level overview of the final schedule of activities for the last 16 days before EI. During this phase, several key decision 'Go/No-Go' meetings were planned during the final week preceeding SRC release, as listed below:

- TCM-12 Go/No-Go – 9/15 (EI-9 days), 11:00p UTC, 5:00p MDT

- TCM-13 Go/No-Go – 9/21 (EI-3 days), 08:00p UTC, 2:30p MDT
- Collision Avoidance Maneuver (CAM) Go/No-Go – 9/23 (EI-21 hours), 18:00 UTC, 12:00p MDT
- SRC Release Go/No-Go – 9/24 (EI-7 hours), 08:00a UTC, 2:00a MDT
  - SRC release command uplink no later than (NLT) EI-6 hours

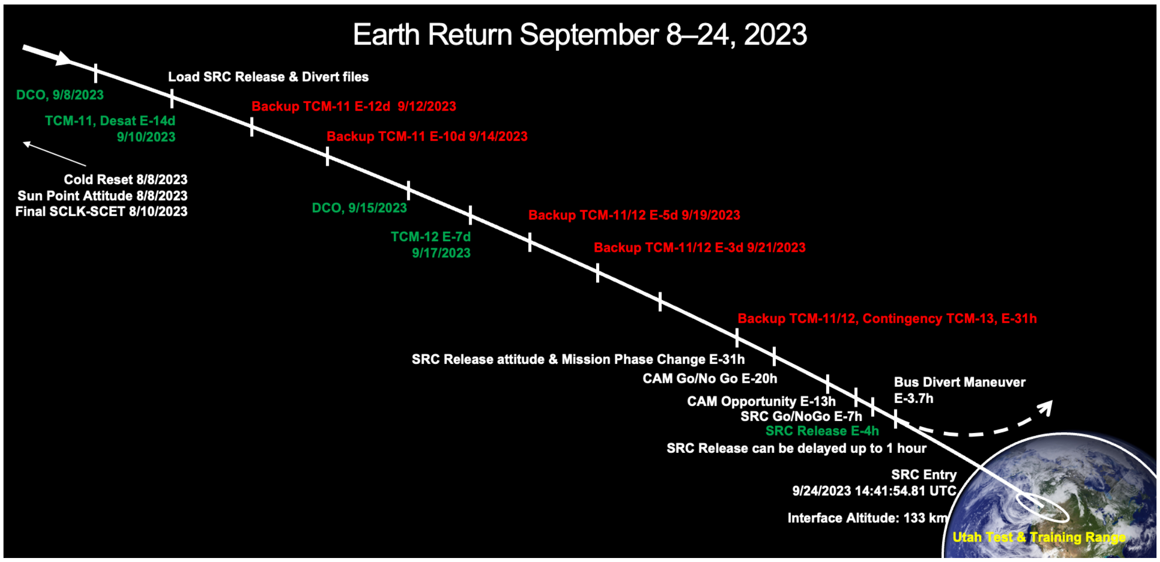

Figure 4: TCM-11 through Entry Descent and Landing Activities

TCM-11 was scheduled 2 weeks before entry on September 10, 2023 at 17:00 UTC. The preliminary OD DCO and design were on August 28, 2023. The Maneuver Performance Data File (MPDF), which contains the latest spacecraft mass and thrust levels, was delivered before the preliminary design. The final OD DCO and design were performed 2 days before TCM-11 execution, on September 8, 2023.

This '48-hour' maneuver build schedule is illustrated in Figure 5. The same schedule was planned for TCM-12 and, in case of contingencies, for all backup TCM-11, -12 opportunities. The schedule began with the DCO at approximately 8:00a MDT, with 2–4 hours allocated for OD processing. A review of the OD solution was performed prior to delivering to the maneuver design team. The OD process typically took less time than allocated, typically with 30 to 45 minutes of margin, due to the incremental nature and stability of the OD solutions. Next, 1–2 hours was allocated for the maneuver design process to produce the final TCM design, documented in a Maneuver Profile File (MPF), run corresponding MC analyses, and generate and deliver ESFs to the EDL team. After receiving the ESF, the EDL team then used it to initialize SRC trajecotry propagations and MC runs through atmosphere and landing using POST2. Results of the MC analyses were compiled to evaluate the range of aerodynamic and aero-thermal loads, landing dispersions, touchdown velocities, and other key metrics. The nominal landing location, as well as the dispersion ellipse size and orientation, were documented in a Landing Location & Ellipse (LLE) file that was delivered to FDS and, as necessary, the recovery team. The LLE file also contained the difference between the desired and achieved mean landing location (latitude and longitude), which could be used by the maneuver design team to adjust EI targets, if needed. Maneuver design and EDL analyses were reviewed

together, nominally concluding around 2 hours after ESF delivery. A typical design and analysis cycle would nominally end by 5 or 6p MDT if only a single FDS-EDL iteration was required.

In the event that the mean touchdown location was significantly off from the desired target, the schedule included enough time for at least one full design iteration between FDS and EDL. Starting with delivery of the LLE containing the recommended EI target adjustments, the maneuver design team would re-target the maneuver and re-run the corresponding MC analyses. The EDL team would subsequently repeat the MC analysis to the ground and a second maneuver design and EDL review would be held to discuss the results. If a second iteration was required, the daily schedule would nominally conclude with product deliveries around midnight MDT. The process to update the EI target was exercised only once during operations, prior to the TCM-12 final design, as described in Reference 9. In that instance, FDS and EDL trended and analyzed TCM-12 designs corresponding to the original and updated EI targets parallel in the days leading up to the final design. Therefore, the TCM-12 delivery schedule occurred well before midnight and much closer to the typical delivery time for a single iteration around 5p MDT.

Regardless of whether a second iteration was required or not, the daily design process concluded with FDS and EDL external product deliveries to the SCT, Conjunction Assessment Risk Analysis (CARA), the recovery team, and other entities, as required.

The next morning, typically at 8a MDT, FDS presented the design and associated analyses during a meeting with the SCT. Afterward, the SCT produced the spacecraft commands and configuration files and documented them in a Maneuver Implementation File (MIF), which included the burn magnitude, duration and direction. MIFs were typically delivered to FDS around mid-day, and FDS would evaluate the MIF parameters against the design values and verify the trajectory propagation. Assuming no issues were identified during the FDS or other subsystem reviews, the maneuver commands were approved during a Command Conference (CC) later that afternoon. Finally, the commands were uploaded to the spacecraft during the next available pass. With near-continuous DSN coverage leading up to entry, there were typically up to 15 hours of DSN contacts available for uplink during the 18-hour period prior to the maneuver sequence.

The decision to perform TCM-12 was based on the following criteria: (a) the design ΔV was $\geq$1.5 mm/s, the approximate limit of navigation accuracy at the time of the TCM-12 design, and (b) the spacecraft was healthy and able to perform the maneuver. This criteria provided additional margin to the EFPA and landing ellipse requirements in the event of a contingency, such as a delayed SRC release. The minimum ΔV threshold of 1.5 mm/s was selected to remain above our approximate trajectory prediction accuracy at the TCM-12 design DCO.

The preliminary design process for TCM-12 began one day after the execution of TCM-11 with a sufficient quantity of tracking data for its initial reconstruction on September 11 (EI-13 days). A preliminary TCM-12 design of 2.4 mm/s was above the 1.5 mm/s threshold and large enough to significantly improve EI targeting. The project held daily status meetings beginning on EI-5 days, following the nominal reconstruction of TCM-12. Daily statuses included a review of FDS and EDL analyses and results and a discussion of the current SRC release criteria status. Beginning at EI-3 days, daily statuses also included a discussion of CARA screening results and CAM maneuver options.

The TCM-12 final design occurred on September 15 and also utilized the ‘48-hour’ schedule described above and shown in Figure 5. The entire design, analysis, and review process was completed by roughly 5:00p MDT. Similar to other design cycles, FDS and EDL provided frequent

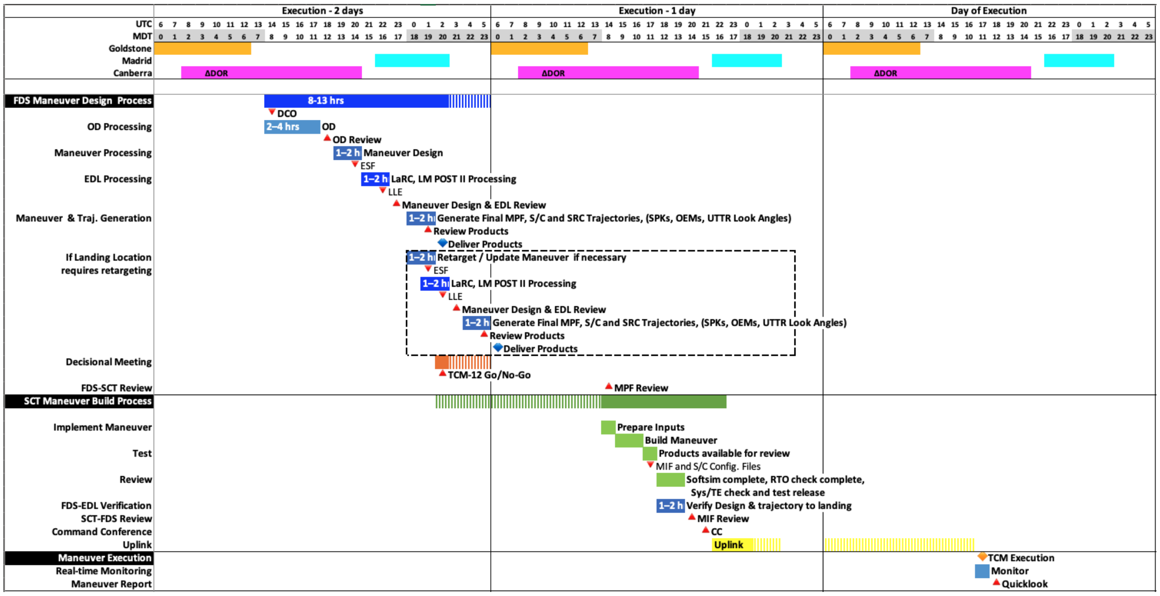

Figure 5: The baseline '48-hour' update process including FDS, EDL, and SCT activities. Actual operations timelines varied slightly day-to-day depending on the specific operations activities, analysis cases, and product deliveries.

status updates to the SCT in order to start the build process as soon as possible and retain schedule margin.

Each day following execution of TCM-11, the navigation team updated the OD and TCM-12 design (up to the final DCO) and ran 4–6 separate MC cases including: the nominal with latest TCM-12 design, without TCM-12, with a 1-hour delayed SRC release, with each of the three possible CAMs, and other miscellaneous alternate cases.[9] ESFs corresponding to each of these cases were analyzed and evaluated by EDL. Although it was not required in actual operations, the last chance for designing and building a contingency maneuver, TCM-13, was scheduled EI-3 days on September 21. If needed, TCM-13 would have executed at EI-31 hours, just before the spacecraft slewed to the SRC release attitude. The operations schedule for the last 3 days of Earth return and entry is shown in Figure 6.

At EI-21 hours, a CAM Go/No-Go meeting was held to determine if 1 of the 3 pre-built CAMs was needed to avoid a potential conjunction between either the spacecraft or SRC and another spacecraft or debris object (see CARA Considerations subsection, below). Beginning on EI-11 days, FDS delivered sets of Earth-centered trajectory and covariance files in Orbit Ephemeris Message (OEM) format to CARA for screening. Prior to EI-3 days, two OEMs were delivered: one for the spacecraft and one for the SRC. At EI-3 days, the number of OEMs increased to 8 and included the nominal plus 3 CAM design options for both the spacecraft and SRC. The last required OEM delivery in support of the CARA screening and CAM Go/No-Go decision meeting at EI-21 hours had an original DCO of September 22 (EI-2 days), as shown in Figure 6. A 'best effort' delivery was scheduled early on September 23 (EI-1 day) to provide one final trajectory and screening update, if feasible. Due primarily to the OD team's efforts to streamline and automate the OEM generation process, the 'best effort' delivery was completed successfully on the morning of September 23 with sufficient time for an additional CARA screening prior to the noon MDT CAM Go/No-Go meeting.

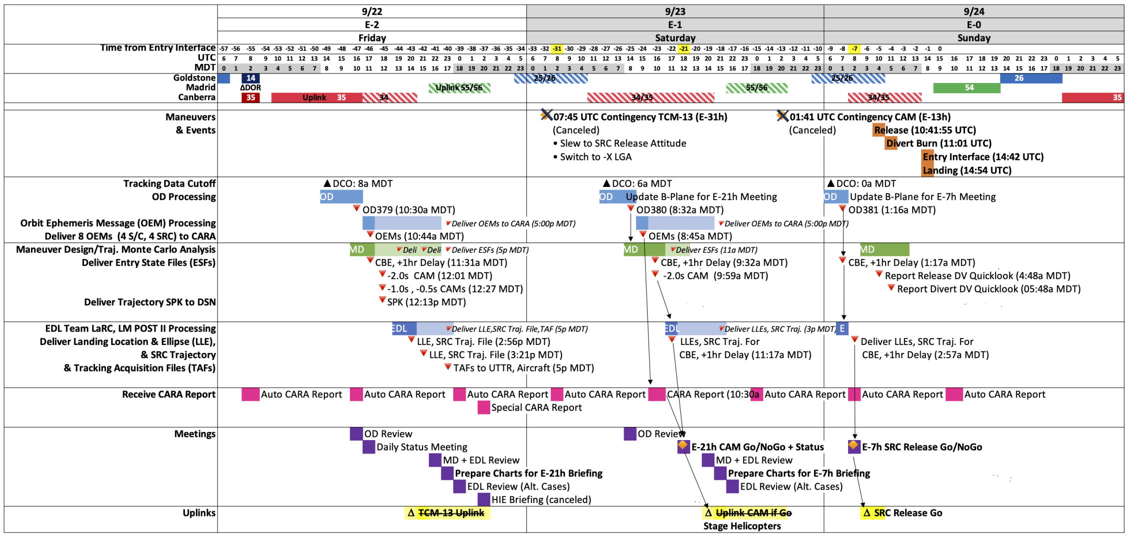

Figure 6: Full operations schedule for the last 3 days of Earth Return including EDL.

SRC Release

The EI-7-hour SRC Release Go/No-Go Meeting occurred at 2:00a MDT (approximately 3 hrs before release, 7 hrs before EI) and included an assessment of the release criteria discussed below for the nominal and 1-hour delayed-release scenarioes. The successful outcome was referred to as the 'Green button,' similar to past robotic sample return missions, Genesis and Stardust.[13] The final FDS-EDL evaluation was performed during the 2 hours preceding the EI-7-hour meeting and including tracking data up to 11 hours before SRC release. Following successful confirmation at the Go/No-Go meeting, an official poll was performed on-console and on the voice network including the Chief Safety Officer, Mission Systems Engineer, Mission Operations Manager, and Project Manager prior to uplinking the 'Green Button' command. All spacecraft subsystems and the "ACE" (the operations team point-of-contact with the DSN) were polled on the voice network prior to the EI-7-hour meeting and gave a 'Go'.

The SRC release decision criteria were arranged into the following categories: FDS, EDL, UTTR, spacecraft, and mission operations.

The FDS criteria were defined as follows:

- Spacecraft maneuver performance has placed the spacecraft on the appropriate trajectory for SRC release, entry, and landing compliant with the landing accuracy criterion.
- OD solutions are consistent and reliable.
- No unmodeled/unknown perturbations have acted on spacecraft.
- Solutions are otherwise reliable/within previously-analyzed regime.
- FDS is ready to support operations.

The EDL criteria is divided into "accuracy" and "SRC survivability" criteria. For both criteria, the EDL team assessed specific EDL metrics from their propagation of the latest ESF states delivered

by the FDS team from entry through the atmosphere and landing. MC statistics for the aero-thermal conditions, peak heating loads, parachute deploy conditions, touchdown speeds, and landing dispersions were compared to the EDL requirements. For touchdown accuracy, 99% of all MC cases were required to fall within the designated safe landing region at UTTR known as the Reference Landing Area (RLA). For SRC survivability, 99% of MC cases were required to comply with peak heat rate (1051 W/cm^2), integrated heat load (30.3 kJ/cm^2), and peak deceleration (40 g's) limits. For peak heat rate and integrated heat load, however, POST2 uses a Sutton-Graves convective heat transfer model.[14] Therefore, when evaluating the POST2 values against the release criterion, mapped limits of 763.3 W/cm^2 and 24.4 kJ/cm^2 for peak heat rate and integrated heat load were used to account for the lack of radiative heat transfer modeling (see Reference 10).

An independent technical panel, consisting of representatives from NASA and Lockheed Martin, was available to adjudicate waiver requests for violations to the release criteria. Fortunately, that process was not needed in operations.

On September 24, 2023 at approximately 4:42a MDT, the SRC was successfully released from the spacecraft and began the roughly 4-hour free-flight to the Earth's atmosphere. The navigation team monitored 2-way Doppler residuals during release, as well as the divert burn 20 minutes later. At roughly 8:42a MDT, the SRC reached EI and began the descent to the surface, eventually landing within the RLA at UTTR a few moments later. The SRC landed approximately 12 km from the target location, but still within the final 99% landing ellipse generated prior to the Go/N-Go meeting. As discussed in Reference 10, the primary contributor to the landing error was a lighter-than-predicted upper atmospheric density. A comparison of the actual landing location versus the target is shown in Figure 7. Additional discussion regarding the final trajectory targeting, OD reconstruction and EDL performance are provided, respectively, in References 8, 9 and 10.

Post-Divert and -EDL

The spacecraft radiometric tracking continued via the DSN through the divert burn; the spacecraft switched from the -X LGA to the +X LGA to maintain continuous coverage of the maneuver. The DSN continued to track the spacecraft after the divert burn, but was not able to acquire 2-way tracking for a few hours near Earth close approach on September 24. During this time, the 200 W minimum uplink power from the DSN could have potentially damaged the spacecraft transponder. Afterward, on September 25 at approximately 11:00 UTC, the spacecraft transitioned back to the 'cruise phase' configuration with the nominal Sun-point attitude and telecommunications over the +X LGA for the OSIRIS-APEX extended mission.[12]

At this point, the navigation team targeted a reference trajectory to enable rendezvous with the near-Earth asteroid 99942 Apophis in April 2029. Based on maneuver analyses, the optimal (i.e. minimum ΔV) epoch for a post-divert clean-up maneuver was at the end of October 2023. The clean-up maneuver, TCM-14, executed on October 23, 2023 17:00 UTC. The DCO for this burn was scheduled one week earlier on October 16. After September 25, the navigation team nominally received one 8-hour tracking pass per day through the TCM-14 DCO and three ΔDOR passes per week. After the Earth flyby, the E-W baselines became available again through the end of 2023. The navigation tracking schedule was reduced to 3 passes per week through June 2024. Tracking will increase for the DSM-1 maneuver planned for June 2024.

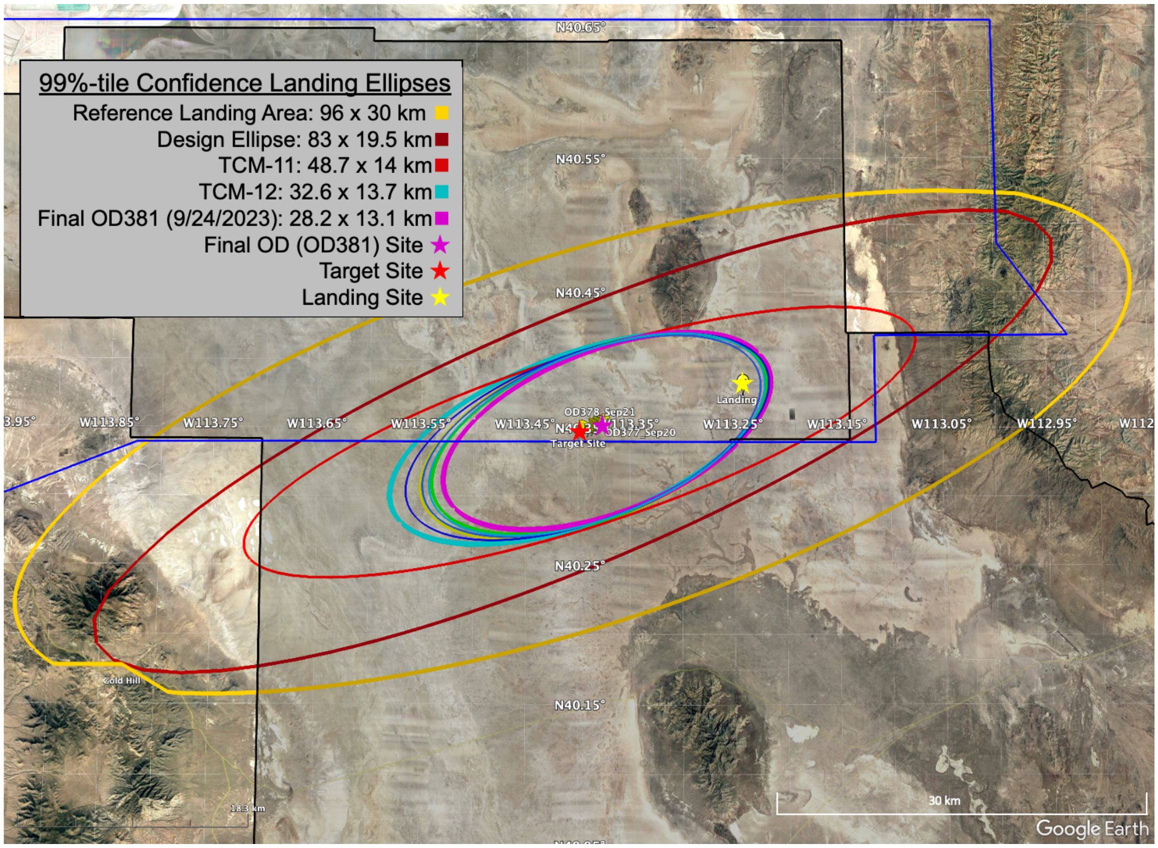

Figure 7: Illustration of landing footprint metrics (Design Ellipse (DE), RLA, and UTTR Restricted Airspace). Includes the landing ellipses corresponding to TCM-11, TCM-12, and the final OD prior to entry (OD381). The target and actual landing sites are indicated by red and yellow stars, respectively.

Interfaces

Figure 8 illustrates the various interfaces both within the OSIRIS-REx Project and with outside institutions that were required for successful EDL operations. Interfaces were documented formally via Operational Interface Agreements (OIAs) and Software Interface Specifications (SISs).

CARA Considerations

OSIRIS-REx was required by NASA Procedural Requirement (NPR) 8079.1 to perform CARA. This process utilizes screening data provided by the United States Space Force (USSF) 18 Space Defense Squadron (SDS) to identify close approaches between NASA assets and other objects in the satellite catalog. CARA then takes the close approach results and determines the level of risk associated with each, providing a recommendation on whether to remediate (if applicable) and supporting analysis products. Previous interaction between OSIRIS-REx and CARA occurred during the 2017 Earth gravity assist (EGA) en route to Bennu. However, the Earth return phase was more complicated than EGA from a CARA perspective because: (1) the risk of a conjunction had to be factored into the decision criteria for SRC release, and (2) both the SRC and the post-divert spacecraft required screening.

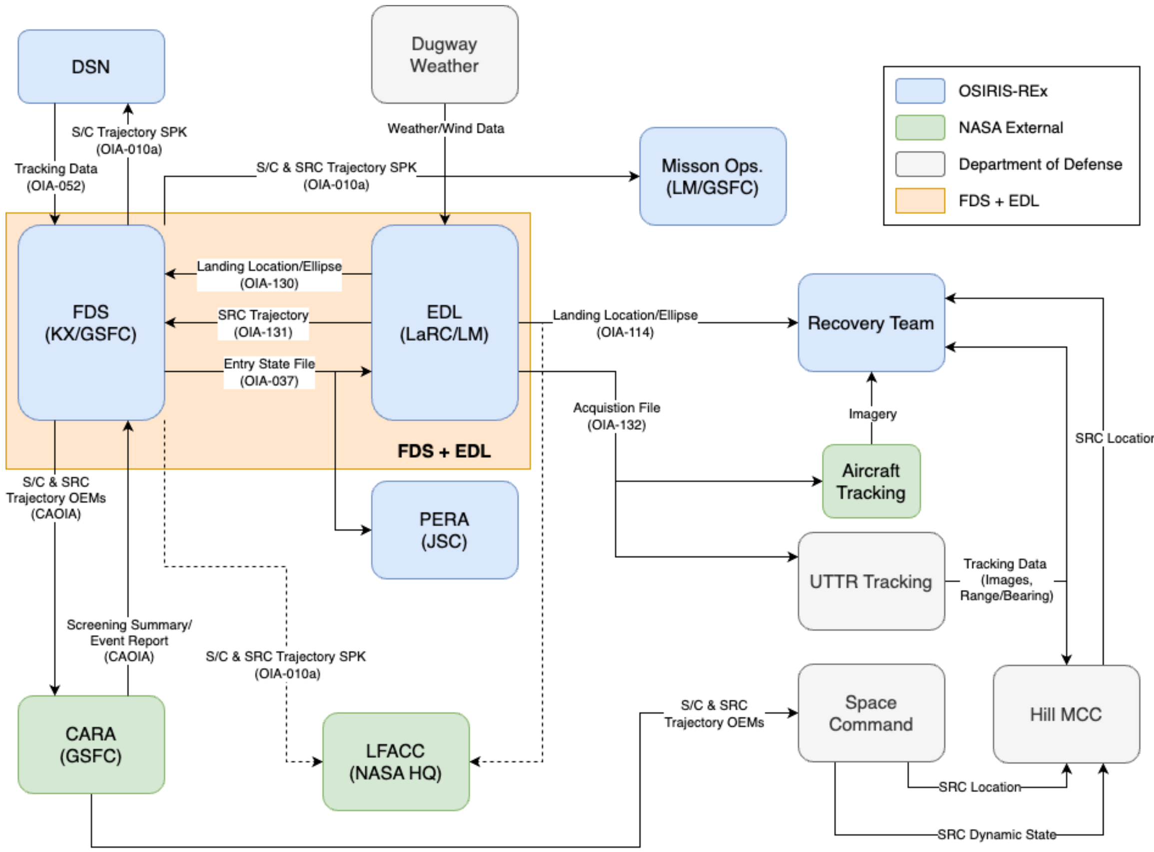

Figure 8: Earth Return & Entry Interfaces.

For Earth return, the mission pre-built and uploaded three CAM options to change the timing of SRC entry by -0.5 sec, -1.0 sec, and -2.0 sec (see Table 3), i.e., an earlier arrival. The CAM burns were designed to adjust the arrival time of the SRC at EI, where the time of perigee passage for the spacecraft bus is similarly changed without being targeted directly. The timing changes were chosen based on a post-divert MC analysis which suggested a 1σ Time of Closest Approach (TCA) uncertainty of approximately 0.5 second. The CAM strategy was selected after a lengthy trade study that involved the FDS, Guidance, Navigation, & Control (GNC), and EDL teams, taking into consideration the effects on landing ellipse and burn attitude effects (e.g., power, slew durations, and Sun Keep-Out-Zone (KOZ) on sensors).

Table 3: CAM maneuver options for 2023 Earth return

Option	Δt (sec)	Δv (cm/s)	ΔPos (km)
1 (TCM-13a)	-0.5	7.6	6
2 (TCM-13b)	-1.0	15.2	12
3 (TCM-13c)	-2.0	30.4	24

The mission based the decision on whether to perform a CAM on the probability of collision

P_c computed by CARA for individual conjunctions. NPR 8079.1 sets forth a P_c value of 1e-4 as the (red) threshold above which a NASA mission must maneuver (if capable) to remediate a conjunction. In general, if the P_c was above 1e-4 for either the spacecraft or SRC at the CAM Go/No-Go time, then the decision would have been 'Go' to perform CAM. However, there are exceptions considered (see Figure 9) such as maneuverable secondary objects that would assume the burden of remediation and CAM trajectories that violate safety constraints that supersede the collision risk. Also, given the spacecraft and SRC having separate trajectories, there was potential, however remote, for none of the options to be free of high-risk conjunctions for both objects. Having multiple CAM options significantly reduced the already low likelihood of that occurring.

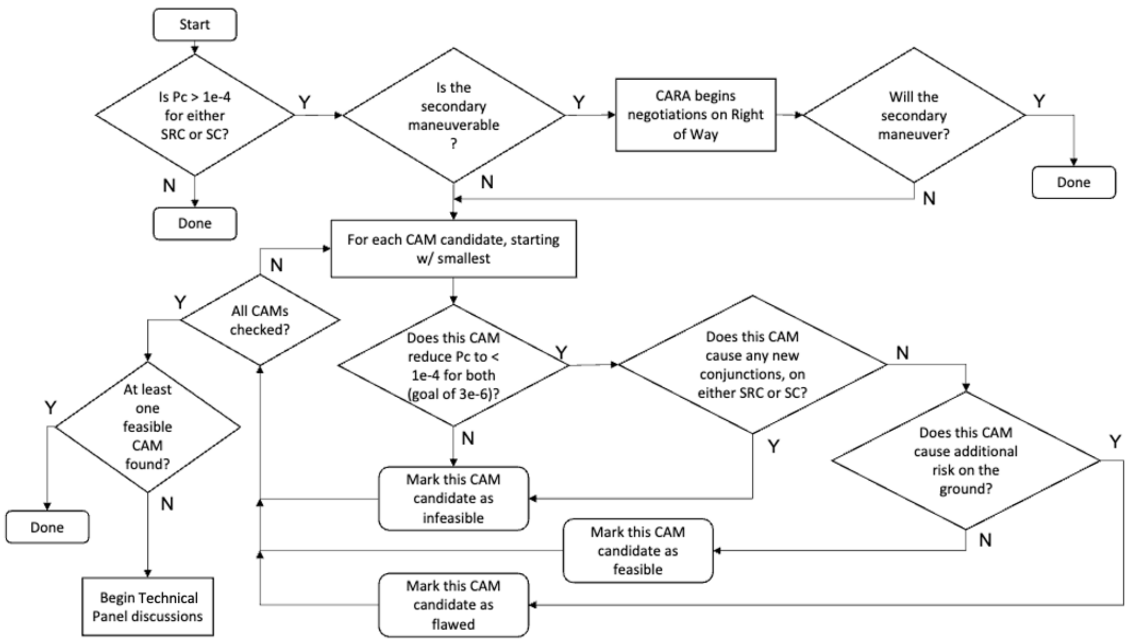

Figure 9: Decision flow chart for selecting a feasible CAM, if needed, from the list of candidate CAMs.

CARA screenings began at EI-11 days on September 13, with twice-daily reports delivered to FDS. From this time until entry on September 24, there were no red or yellow conjunction events for either the SRC or the spacecraft bus. Thankfully, no conjunctions were identified and none of the CAM burns were needed during operations.

OPERATIONS TRADES

This section outlines the project-level trades and alterations of the original, pre-launch design and ConOps made prior to Earth return and entry. Following successful TAG, the OSIRIS-REx project investigated a number of design changes, analysis updates, and trade studies with the goal of increasing robustness to contingencies and other surprises. The changes that drove the targeting strategy and performance are summarized below:

- The ADM was moved from March 3, 2021 to May 10, 2021. The May opportunity required less overall ΔV compared to the March departure and provided additional margin for the

extended mission. The new trajectory increased the entry velocity from 12.2 km/s to 12.36 km/s, and changed the entry azimuth (and thus the ground error ellipse orientation) by approximately 5°.

- The maneuver execution error values for the ACSTBT thruster suite were updated based on operational performance and subsequent simulations by the GNC subsystem. Similarly, in-flight performance was used to update OD and trajectory prediction accuracy. A series of LTR and ACSTBT thruster calibrations were added in the summer of 2022 to confirm execution error assumptions. Maneuver execution and OD error assumptions are described in References 8 and 9.

- Per requirement FDS-F-32, the Earth targeting strategy incorporated biased Earth B-Plane targets for TCM-9, executed in September 2022, and TCM-10, executed in July 2023, to ensure negligible probability of impact with Earth given no future maneuvers. Overall improved navigation performance[8] allowed the team to adjust the B-Plane bias altitudes for TCMs-9 and -10, moving them both closer to Earth and subsequently reducing the required deterministic ΔV for TCMs-10 and -11. The targeting strategy for TCMs-9 to -11 is described in the Earth Return Targeting Strategy subsection above and in Reference 9.

- At the recommendation of the navigation team, the schedules for the final deterministic targeting maneuver, TCM-11, and the associated statistical clean-up, TCM-12, were 'ventilated' to provide additional margin and back-up opportunities. TCM-11 was moved from EI-7 days to EI-14 days. TCM-12 was moved from EI-31 hours to EI-7 days. The design for TCM-12 would have included a single maneuver decomposition strategy to avoid KOZ violations without the added complexity of two-maneuver decomposition sequences (see Reference 9). However, the actual TCM-12 design was well outside the KOZ and decomposition was not necessary. Compared with other recent interplanetary sample return missions, OSIRIS-REx had the longest time span (7 days) between the final TCM prior to capsule release and entry; Stardust,[13] Genesis,[15] Hayabusa,[16] and Hayabusa2[17] occurred at EI minus 1.2, 2, 4, and 4 days respectively.

- The final momentum desaturation prior to EDL was placed on EI-14 days, 90 minutes after the nominal TCM-11 epoch, and would have executed even if TCM-11 did not. The placement balanced momentum management requirements, trajectory perturbations, and error propagation time. The desat was biased to minimize wheel saturation prior to EDL.

- Three contingency CAM maneuver designs were developed to shift the time of SRC arrival at EI by -2.0s, -1.0s, or -0.5s in the event that the CARA screening produced a red event for the SRC or spacecraft with the nominal trajectory prediction. The CARA screening process and CAM maneuver designs were described in the CARA Considerations subsection above.

- In order to ensure that the spacecraft safely flew by the Earth after SRC release, the spacecraft fault detection system had the capability to automatically restart the divert burn if it did not fully complete. Maneuver design analyses indicated that it was only necessary for 30% of the burn to complete to ensure the spacecraft would miss the Earth in the nominal case, or 42% in the unlikely contingency scenario where the spacecraft autonomously delayed SRC release up to a maximum of 1 hour. Requiring 100% of the burn to execute before transitioning to the next phase, however, would have significantly impacted the extended mission ΔV. Therefore, the navigation and spacecraft teams developed a time-based trigger for divert burn completion

percentage threshold to minimize the impact of a "double divert" scenario while ensuring the spacecraft reached minimum periapsis. Double divert analysis is discussed in Reference 9.

LESSONS-LEARNED

While navigation operations for Earth return and entry were ultimately successful, the team identified a number of navigation and EDL key observations and lessons-learned for future sample return missions, listed below.

Early coordination between the navigation and EDL teams. The hand-off of design and analysis responsibilities at Earth EI necessitated the close coordination between the navigation and EDL teams. Meetings to discuss final preparations for Earth return and entry began in January 2022, approximately one-year ahead of the original plan. This early coordination was driven by the project review schedule; specifically, the Earth Entry Targeting review in August 2022. Scheduling meetings early and often allowed for additional time to perform analyses and consider design trades, ultimately improving the robustness of the design considering realistic contingencies. Personnel, processes, and interfaces were well-exercised by the time of entry operations.

Entry interface targeting strategy; ability to perform navigation spot-checks and targeting to the ground. Earth EI proved to be a convenient and logical point to delineate design and analysis responsibilities between navigation and EDL teams and allowed each of the respective groups to focus on and apply their expertise and tools. The ESF and LLE interfaces provided a convenient means for transmitting analysis information and operational deliveries among the two groups. However, this interface required an iterative process to perform operational maneuver design and Earth EI targeting analyses. The ability for the navigation team to propagate the SRC all the way to the ground, even with medium- or low-fidelity models, would have been useful as an initial check of maneuver design performance, as well as a means to perform quick and efficient sensitivity and off-nominal analyses without requiring a full iteration with the EDL team. Official information regarding the SRC landing location and dispersions, as well as aerodynamic and aerothermal performance, should still come from the EDL team using high-fidelity, formally-verified, 6-DOF simulation software (e.g. POST2). The recommendation to have an independent, integrated maneuver design and EDL tool was proposed by the Earth Entry Targeting review panel, but the navigation team was not able to develop new and/or modify existing software in the time available prior to entry.

Well-ventilated primary and back-up maneuver schedule. The decision to "ventilate" the terminal targeting maneuver timeline, i.e. move TCMs -11 and -12 to EI-14 and -7 days, respectively, was made to provide sufficient schedule margin to perform at least two back-up opportunities for each maneuver while maintaining the 48-hour design cycle. The original schedule placed the final targeting maneuver, TCM-12, at EI-31 hours in order to meet EI and landing accuracy requirements. However, navigation performance demonstrated in-flight was significantly better than assumed prelaunch and indicated requirements could be met with a more ventilated schedule. Fortunately, all maneuvers executed nominally and back-up opportunities were not needed; nonetheless, the additional margin would have been useful in the event of an anomaly to provide as much time as possible to diagnose and correct any issues on the spacecraft. The ventilated schedule also circumvented the need for the navigation and operations teams to design contingency burns in parallel; instead focusing on the primary maneuver designs and only proceeding with back-up designs in the event that the primary maneuver did not actually execute. See Reference 9 for more information on the back-up maneuver strategy.

Ability to perform ultra-fine (mm/s-level) maneuvers on the LTR thruster suite for terminal targeting. Another early spacecraft design decision that enabled both the ventilated schedule and ultra-precise entry targeting was the inclusion of the LTR thruster suite. LTRs were added during development primarily to accommodate mm/s-level phasing maneuvers in the μg environment at Bennu.[2,18] The ability to perform small maneuvers was necessary for executing TCM-12 at EI-7 days given the additional propagation time and thus increased control authority. The final design ΔV for TCM-12 was 3.093 mm/s (3.033 mm/s reconstructed).[9] Having multiple thruster suites with overlapping ΔV capability provided additional flexibility in the overall maneuver targeting strategy and improved performance.

Incorporation of weather predictions in the design of the final targeting maneuver. On the other hand, one of the drawbacks to executing TCM-12 at EI-7 days was that it precluded the use of updated weather predictions, specifically atmospheric density and wind data, in Earth entry targeting. The EDL team relied primarily on the Global Reference Atmosphere Model (GRAM)[19] to provide atmospheric and weather data for 6-DOF modeling of the SRC during descent, which is generated using long-term averages and dispersions. While ideal for assessing the likely and range of possible conditions in analyses prior to entry, GRAM does not incorporate up-to-date predictions available from various sources. Variation in these conditions are a significant contributor to SRC landing dispersions, and become a dominant error source as the SRC approaches EI and navigation dispersions decrease. Conversely, atmosphere/weather predictions at 7 days out from entry are typically not reliable or accurate enough to have justified inclusion in the TCM-12 design cycle. Therefore, future missions may want to trade the operational convenience of placing the final Earth targeting maneuver as far out as possible versus the potential increase in landing accuracy due to shorter propagation times and the inclusion of updated weather predictions. In hindsight, nominally executing TCM-12 closer to entry, e.g. EI-4 days, and incorporated updated weather predictions for OSIRIS-REx sample return may have warranted consideration. Additional information on the EDL analysis process and impact of atmospheric density and wind predictions can be found in Reference 10.

Formal interface for SRC release attitude and update process. For aerodynamic and aerothermal reasons, the EDL team desired a nominal angle of attack (AoA) of 0° when the SRC reaches an altitude of 100 km. While the SRC will naturally tend to trim to 0° AoA, larger initial dispersions would likely lead to larger oscillations about the nominal attitude. The GNC team designed the spacecraft attitude at the time of SRC release to achieve the desired SRC attitude and AoA conditions, provided as an inertial vector from the EDL team. The maneuver design team, in turn, used the SRC release attitude quaternion from GNC to define the release ΔV direction. However, neither of these products were defined as a formal interface, which led to some confusion during the final update a few months prior to entry. It was discovered that the 5° entry azimuth change due to the May 10th asteroid departure caused the SRC release attitude to move the instrument deck 5° further into the solar KOZ. While the project ultimately determined the risk to the instruments was negligible and accepted the attitude change, it caused additional analysis and verification work relatively late in the design cycle. The recommendation for future missions is to define the 0° AoA inertial vector and SRC release attitude as a formal interfaces and plan more frequent updates, particularly when entry conditions change.

Range coordination and defining a clear landing accuracy criterion and/or acceptable landing region. Successful landing and recovery required close and frequent coordination between OSIRIS-REx and the UTTR. One of the most critical areas of understanding was the definition of

an acceptable landing region within the range. The original acceptable landing ellipse defined prior to launch, known later as the DE, was based on expected landing dispersions generated through navigation and EDL MC analyses using pre-launch assumptions in performance. This ellipse, however, did not consider the landing area knowledge at the time of the release decision or reasonable contingency scenarios, such as a late SRC release. Revisiting the topic prior to entry, OSIRIS-REx and UTTR reached an agreement on a new acceptable landing region known as the RLA. The dimensions of the RLA account for credible off-nominal scenarios and uncertainty in the predicted landing location at the time of SRC release decision, as well as populated areas on the ground. In order to release the SRC, 99% of the predicted SRC landing locations had to fall within the RLA. The RLA provides enough margin to maximize the likelihood of a positive release decision without adding unreasonable burden on UTTR to certify the acceptable landing region. Dimensions of the DE and RLA relative to the extent of the UTTR restricted airspace is shown in Figure 7. The two organizations also developed a process by which the range could approve a landing location and ellipse that fell outside of the RLA given at least a few days notice and the process was exercised during an off-nominal ORT. Fortunately, the actual predicted landing ellipse at the time of the SRC release decision was well within the RLA and this waiver process was not needed. The RLA and landing performance is discussed further in Reference 10.

Understand OD parameter observability; EI and EDL parameter sensitivity. Prior to and during entry operations, the OD, maneuver design, and EDL teams performed various simulations and analyses to assess the relative contribution of various error sources to the overall OD uncertainty, EI dispersions, and landing ellipse size. Knowledge of the relative impact of each perturbation provided valuable insight to the navigation and EDL teams, indicated where effort should be spent to improve performance, and which error sources required less attention.

The OD team produced and compared multiple operational solution sets with unique measurement combinations, weighting, and stochastic acceleration assumptions. A useful reference was the relative contributions of various error sources, including maneuver execution error, measurement noise, media calibration, etc., relative to the Earth entry B-Plane. The reliance on N-S ΔDOR baselines, or more specifically the lack of E-W baselines, led to limited observability in certain parameters leading up to entry, notably the maneuver pointing for TCMs -11 and -12. While this was not an issue given the *a priori* pointing performance demonstrated throughout flight, it was important to understand the limitation in the available data to directly measure certain parameters. The OD team also observed a sensitivity to the daily troposphere and ionosphere calibration file updates provided by the DSN. Unfortunately, in order to meet the 48-hour update schedule, the OD delivery occurred prior to the receipt of the updated calibration files from the DSN. Future missions may want to consider negotiating an earlier delivery time with the DSN and/or adjust the daily OD DCO to incorporate the latest deliveries. See Reference 8 for more details on OD performance.

Similarly, the maneuver design team performed parametric MC analyses to determine the relative contribution of error sources to the expected SRC dispersions at EI. Error sources considered included OD state knowledge, maneuver execution error, SRC release translational error, residual ΔV from momentum desaturations, and spacecraft and SRC stochastic non-gravitational accelerations. Following TCM-12 execution, OD knowledge error was the most dominant contribution, followed by SRC release translational error. See Reference 9 for more details on trajectory dispersions at EI.

The EDL team also performed a similar parametric MC study, considering atmospheric density, wind, SRC state (or EFPA) dispersions at EI, sample mass, and SRC center-of-gravity (CG) loca-

tion. Spacecraft state/EFPA dispersions had the largest impact on the landing ellipse, followed by wind and atmospheric density. Variation in the sample mass and SRC CG location had negligible impact on landing dispersions. EDL analyses are discussed in more detail in Reference 10.

Understand SRC release dynamics and error statistics (translation and rotation). At EI-4 hours, the SRC was released from the spacecraft by a spring-loaded separation-spin mechanism. Accurate SRC targeting required knowledge of the ΔV (magnitude and direction) applied by the separation-spin mechanism. High-fidelity, multi-body MC dynamical simulations of the separation-spin release were performed by the spacecraft team prior to launch for "ambient" and "cold" temperature cases. The data generated by the MC was used to provide release statistics (mean and standard deviations) to the maneuver design team for pre-launch analyses. However, it was difficult to revisit and interpret the data and statistics prior to entry given the long duration and personnel attrition, among other factors. The team was also not able to re-run the original high-fidelity dynamical simulations to reproduce/re-analyze the results. It was also important to clearly define the frame in which the ΔV is applied, and whether it was expressed as an absolute or relative ΔV between the spacecraft and SRC. Ultimately, the reconstructed ΔV was much closer to the "cold" dataset than the "ambient," even though mechanism temperatures were well within "ambient" levels (see Reference 8). Having a good understanding of the release mechanism dynamics, well-documented assumptions and statistics, and the ability to re-visit high-fidelity simulations throughout the mission (incorporating information gained during flight) are notable lessons-learned for future sample return missions.

Revisit landing analysis periodically throughout operations. One of the unique aspects of sample return and similar missions is that they contain multiple sub-phases with unique operational and navigation requirements. Extensive analyses on Earth entry targeting and EDL were performed during the design and development phase to verify system performance prior to launch. Following launch, the operations team turned their attention to the cruise and asteroid proximity operations phases. Earth return and EDL analyses were not revisited until after successful sample collection. Although the navigation and EDL teams began preparations nearly two years prior to entry, it would have been worthwhile to periodically revisit the topic throughout operations to refresh the team, familiarize new personnel, and exercise tools and processes. In the case of some special analyses, including the separation-spin modeling mentioned above and aero-thermal/structural analysis and maximum limits for the SRC, it may have been useful to re-run and re-analyze prior to entry. However, in both cases, the time elapsed and start-up effort were too prohibitive given the schedule and resources leading up to sample return. Explicitly including time and resources to revisit these and similar analyses would alleviate these difficulties for future missions.

Non-linear MC vs. Linear Covariance for EI state dispersions. For the majority of Earth return and entry operations, maneuver and EI dispersion analyses were performed using a full non-linear MC analysis as described in Reference 9. While full non-linear propagation of randomly perturbed states and error sources with maneuver guidance updates provide the most accurate representation of trajectory dispersions, it was time-consuming and computationally-intensive to produce 3000+ realizations for each scenario. Following TCM-12 execution, the maneuver design team also had the capability to produce an ESF using an OD covariance mapped to EI, which was significantly faster than running a full MC (minutes versus hours). This technique was used as the input for the final SRC landing ellipse MC at the EI-7 hrs Release Decision Meeting. Having the ability to perform linear covariance analyses that include guidance and full state dispersions would be useful for future missions as a compliment to full non-linear MC, particularly when analyzing alternate

operations strategies and contingency scenarios.

Clear and concise release criteria for FDS and EDL. SRC release criteria for the various elements were discussed extensively across all mission elements. The goal was to maximize the probability of release while ensuring the SRC survived entry and posed no danger to people or property on the ground. While there was a feasible trajectory design for a back-up sample return attempt in 2025, the close approach to the Sun (approximately 0.5 au) meant the sample viability would likely have been compromised, and there was no guarantee the spacecraft would survive those extreme thermal conditions. One option was to use EFPA dispersions as a proxy for SRC survivability. The team looked to define an expanded EFPA beyond the original MRD requirement of $\pm 0.08^\circ$ 3σ, since it was likely the SRC would survive well beyond those limits. Ultimately, the project decided to use a subset of the overall EDL parameters analyzed during each MC run, specifically peak heat rate, integrated heat load, and peak deceleration because those parameters most directly influence survivability. Parameters affecting parachute deploy, including SRC battery status and deploy altitude and pressure, were not considered given that a hard landing was generally preferred over the 2025 back-up return scenario. In the case of a battery issue, there was likely not anything that could have been done in the intervening two years to resolve the issue, anyway.

With respect to FDS, there was discussion about whether or not there should be specific navigation-related criteria in addition to the EDL accuracy and survivability criteria. The FDS criteria, described in the SRC Release subsection above, were eventually included given that the navigation solution and EI dispersions were the primary input to the EDL MC analysis, and there should be at least a qualitative assessment of those results prior to acting on that data.

CARA and CAM considerations. Objects on intercept or flyby trajectories with respect to Earth are a unique scenario for conjunction assessment, and require special coordination and planning. OSIRIS-REx was fortunate to have a former member of the navigation team transition to a new role on the CARA technical leadership team after TAG, which aided communication and coordination greatly. Clear criteria for executing the CAM, as well as a process for quickly adjudicating potential waivers of that criteria, were established between CARA and the project. The CARA ConOps for OSIRIS-REx should be generally applicable to future missions that feature Earth flybys and/or sample return. In terms of areas of improvement, it was difficult to quantitatively assess the adequacy of the three CAM maneuver magnitudes/time shifts given the wide range of possible conjunction geometries and secondary object uncertainties. This could be a fruitful area of further research and development. While the standard CARA reports were sufficient in communicating that there were no appreciable conjunctions identified, CARA also provided a non-standard, unofficial table that included all objects with a minimum miss distance of roughly 100 km or less from either the spacecraft or SRC. This report provided additional context and confidence and situational awareness. It was also not possible to screen trajectories further than 10 days in advance of EI, which limited the ability to perform end-to-end tests well in advance of entry. Having a test environment for CARA screening may benefit future missions with similar ConOps. Lastly, CARA also performed special analyses to assess minimum orbit crossing distances for all objects in the catalog, which is useful for identifying *possible* conjunctions months versus days in advance.

Spend time thinking about what-ifs, contingencies, and improvements. This was a recommendation at the Earth Entry Targeting review, and was embraced by the entire OSIRIS-REx team. The navigation and EDL teams organized dedicated discussions to address these topics, which resulted in improved processes and robust contingency plans. While Earth return operations were mostly nominal, the team was well-prepared for multiple realistic contingency scenarios and main-

tained a high level of confidence in the ability to respond to unexpected events.

CONCLUSIONS

OSIRIS-REx sample return and recovery was a historic technological and scientific achievement. Precisely targeting and modeling the SRC through the atmosphere and to the Earth's surface required intricate design, careful planning, and extensive analysis by the navigation and EDL teams. Previous missions, including Stardust, Genesis, Hayabusa, and Hayabusa2, provided valuable templates and insights into Earth sample return strategies. While the OSIRIS-REx approach to Earth return and entry was hugely successful, lessons and areas of improvement gathered along the way will likely prove valuable for future sample return missions. Notable findings are provided in this paper, along with a general overview of the targeting strategy and navigation operations plan as a reference for future missions endeavoring to land on other bodies and/or deliver pristine samples from across the solar system safely to Earth.

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